Automatic Estimation of Modulation Transfer Functions

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Automatic Estimation of Modulation Transfer Functions

This project is joint work with

Valentin Volchkov
Michael Hirsch
Bernhard Schölkopf
How good is this lens?

Lens quality is determined by *optical aberrations*.
Optical aberrations are spatially varying
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Optical aberrations can be characterised by the point spread function (PSF)
How good is this lens?

- Lens quality is determined by **optical aberrations** (spatially varying PSF)
- Related and normalised quality measure: **Modulation Transfer Function (MTF)**

**What is the MTF?**
The local MTF characterises diminished relative contrast
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MTF as normalised diminished relative contrast

\[ C(f) = \frac{I_{\text{max}}(f) - I_{\text{min}}(f)}{I_{\text{max}}(f) + I_{\text{min}}(f)} \]

\[ \text{MTF}(f) = \frac{C(f)}{C(0)} \in [0, 1] \]
The local MTF characterises diminished relative contrast

MTF as normalised diminished relative contrast

\[ C(f) = \frac{l_{\text{max}}(f) - l_{\text{min}}(f)}{l_{\text{max}}(f) + l_{\text{min}}(f)} \]

\[ \text{MTF}(f) = \frac{C(f)}{C(0)} \in [0, 1] \]

MTF as Fourier Transform of the Point Spread Function

\[ \text{PSF}(x) \xrightarrow{\mathcal{F}} \text{OTF}(f) \propto \text{MTF}(f) e^{i\text{PhTF}(f)} \]
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MTF as Fourier Transform of the Point Spread Function

\[ \text{PSF}(x) \xrightarrow{\text{FT}} \text{OTF}(f) \propto \text{MTF}(f) e^{i\Phi_{\text{TF}}(f)} \]

Aggregate local MTF values into *global MTF charts*
Aggregate local MTF curves into global MTF charts
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$\text{MTF}_{10} = \text{MTF}(f = 10 \text{ cycles/mm})$

$\text{MTF}_{20} = \text{MTF}(f = 20 \text{ cycles/mm})$

$\text{MTF}_{30}$

$\text{MTF}_{40}$
Global MTF Charts: Radial and Tangential MTF

measure the **radial MTF**

measure the **tangential MTF**

Sigma 50mm f/1.4 EX DG HSM @ f/1.4
Global MTF Charts: Radial and Tangential MTF

measure the radial MTF

measure the tangential MTF

Lens manufacturers provide MTF charts
How good is this lens?

- Large variability between different specimens of the same lens
- Lenses often surprisingly asymmetric

Image Source: Canon
How good is this lens?

How good is your lens? Assessing performance with MTF full-field displays

Brandon Dube,1,2,* Roger Cicala,1 Aaron Closz,1 and Jannick P. Rolland2

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- Large variability between different specimens of the same lens
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Want the MTF curve for a specific specimen of a lens
### Photometric MTF measurements

#### Typical techniques used for lens quality assessment

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<thead>
<tr>
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<tbody>
<tr>
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<td>MTF test charts</td>
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<tr>
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#### MTF test charts

- Several methods:
  - Slanted edge [Burns2000]
  - Dead leaves
  - Siemens stars [Loebich2007]
- DxO, imatest, Image Engineering, ...
Photometric MTF measurements

### Typical techniques used for lens quality assessment

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- wavefront sensor
- professional MTF testing station

#### MTF test charts

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- DxO, imatest, Image Engineering, ...

**Lens quality assessment is laborious and requires equipment**
Our approach: Estimate MTF blindly from photographs

This work: A learning system for MTF estimation from photographs

- Unprocessed photographs
- Learning system
- Distance from centre [mm]
- Global MTF chart
Our approach: Estimate MTF blindly from photographs

This work: A learning system for MTF estimation from photographs

- Photographs contain ample information about lens properties
- Information is confounded with image statistics of unknown scenes
- Lens properties are the same for different motives
Overview of our learning system

Patch extraction  Local MTF estimation  Global MTF aggregation
Overview of our learning system

Patch extraction → Local MTF estimation → Global MTF aggregation

at position \((R, \varphi)\)

in direction \(\varphi\)

MTF

MTF10

MTF20

MTF30

MTF40

0 10 20 30 40

0 1

f [lp/mm]

MTF

0 10 20 30 40

f [lp/mm]

MTF

0 10 20 30 40

f [lp/mm]
Local MTF Estimation: Network Architecture

- **Inputs**: $192 \times 192 \times 1$ image patches
- **Outputs**: MTF10, MTF20, MTF30, MTF40 (tangential and radial)
Local MTF Estimation: Network Architecture

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- **Initial data processing**: Rotation, image gradient, subsampling into channels
- **DNN** with convolutional residual blocks and fully connected layers
- **Treat multiple input patches**
  Compute the intermediate feature representation separately and average them in feature space (similar to “Deep Sets” [Zaheer 2017])
Train the Local Estimation Network on synthetically blurred patches

Set up a supervised training task

<table>
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<th>Input: Synthetically blurred patches</th>
<th>Output: MTF values of the blur</th>
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Required training and validation data:
- Sharp image patches
  - Regular patterns [Joshi 2008]
  - Patches from photos in the wild
- Lens blurs and their MTFs
  - Record lens blurs with custom pinhole array

MTF

f

0 10 20 30 40
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Required training and validation data

### Sharp image patches
- regular patterns [Joshi 2008]
- patches from photos in the wild

### Lens blurs and their MTFs
- Record lens blurs with custom pinhole array
Record ground truth PSFs/MTFs using a self-made pinhole array

- Custom-built pinhole array to efficiently and accurately record PSFs
- Image of a point light source is the PSF
- Record $80 \times 60 = 4800$ PSFs per lens and setting over the entire field of view

New dataset of real PSFs for aberrated lenses
Experiments: Estimate MTF charts from three types of images

1. Synthetically blurred patterns (same as training but with unseen blur)
2. Photographs of printouts of the test pattern (similar to a test chart)
3. Photographs of natural scenes in the wild

All results for the same lens (Sigma 50mm f/1.4 EX DG HSM @ f/1.4)
Results on the test pattern

1 + 2

from real photos (●)

Ground truth

from synthetically blurred images

MTF10  MTF20  MTF30  MTF40

tangential  radial

centre to top right corner

Average error

Estimation from synthetically blurred patches almost perfect (for all lenses)

Very good quantitative and qualitative agreement

Estimation errors for other lenses typically similar
Results on the test pattern

- Estimation from synthetically blurred patches almost perfect (for all lenses)
- Very good quantitative and qualitative agreement
- Estimation errors for other lenses typically similar
Results on natural scenes

- Ground truth
- Estimates from real photos

MTF10, MTF20, MTF30, MTF40

centre to top right corner

Very good qualitative agreement

Good quantitative agreement
3 Results on natural scenes

- Very good qualitative agreement
- Good quantitative agreement
Main sources of discrepancies

- **Curvature of the focal plane**
  
  the PSF panel is completely flat while real objects have depth variations
Limitations and discussion of discrepancies

Main sources of discrepancies

- **Curvature of the focal plane**
  the PSF panel is completely flat while real objects have depth variations

- **Not all patches suitable**
  - Objects not in focus
  - homogeneous/texture less areas (e.g. sky)
  - edges in only one direction
Limitations and discussion of discrepancies

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- **Curvature of the focal plane**
  the PSF panel is completely flat while real objects have depth variations

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Mitigation strategies

- **So far**: Select suitable photographs

- **Future work/Production system**: Automatic patch selection from photographs, similar to “Finding good regions to deblur images” [Hu 2012]
We present a system for MTF estimation from real photographs

Patch extraction Local MTF estimation Global MTF aggregation

- Estimate entire MTF charts from a batch of photographs within minutes
- Good qualitative and quantitative results
- New dataset of real PSFs from aberrated lenses (available on the project website soon)

https://ei.is.mpg.de/projects/mtf-estimation

Questions?
Questions? See you at the poster session!
Appendix/Backup
Results improve with more data

- Increase the number of input patches from the same location but different images
- Patches are averaged in feature space
Treat multiple input patches

<table>
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<tr>
<th>Average in feature space</th>
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<tbody>
<tr>
<td>$y = FC \left( \frac{1}{N} \sum_i CNN(x_i) \right)$</td>
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<tr>
<th>CNN($x_1$)</th>
<th>+</th>
<th>CNN($x_2$)</th>
<th>+</th>
<th>CNN($x_3$)</th>
<th>+</th>
<th>FC</th>
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<table>
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<th>Average in output space</th>
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<td>$y = \frac{1}{N} \sum_i FC(CNN(x_i))$</td>
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$y = \frac{1}{N} \sum_i y_i$
Comparison to other methods

Photometric measurements

State-of-the-art deblurring algorithm
Robustness to noise

![Graph showing the relationship between average estimation error and noise scale σ. The error increases as the noise scale σ increases.](image-url)
Orientation of edges

Average estimation error vs. Rotation angle $\alpha$
Subsampling into channels

Before subsampling: $12 \times 12 \times 1$

After subsampling: $4 \times 4 \times 9$